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THE ANGULAR IMPACT DISTRIBUTION OF CHARGED PARTICLES ATTRACTED --ETC(U)
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ENVIRONMENTAL RESEARCH PAPERS, NO. 741

The Angular Impact Distribution of Charged Particles Attracted to a Charged Cylindrical Spacecraft

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13 May 1981

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FOR THE COMMANDER

John Howard

Chief Scientist

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFGL-TR-81- 14?	2. GOVT ACCESSION NO. AD-A104	3. RECIPIENT'S CATALOG NUMBER 519
4. TITLE (and Subtitle) (6) THE ANGULAR IMPACT DISTRIBUTION OF CHARGED PARTICLES ATTRACTED TO A CHARGED CYLINDRICAL SPACECRAFT.		5. TYPE OF REPORT & PERIOD COVERED Scientific. Interim.
		6. PERFORMING ORG. REPORT NUMBER ERP No. 741
7. AUTHOR(s) (10) Arthur L. Besse, Allen G. Rubin (9) Environmental research papers		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Geophysics Laboratory (PHK) Hanscom AFB Massachusetts 01731		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62101F (16) 76611101 (17)
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory (PHK) Hanscom AFB Massachusetts 01731 (11)		12. REPORT DATE 13 May 1981
		13. NUMBER OF PAGES (12) 12
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) (14) AFGL-TR-81-0142, AFGL-ERP-741		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Spacecraft charging
Impact angle distribution
Cylinders
Spheres
Planes

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The angular distribution of incident particles is obtained for attracted and repelled particles incident on a charged cylindrical spacecraft. The angular distributions are important when backscattering and secondary emission are significant processes. Results are given for planes and spheres as well.

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1. INTRODUCTION

Spacecraft in geosynchronous orbit exhibit charging when immersed in hot substorm plasmas. The potential that a surface attains depends both on the material's properties and on the plasma's characteristics. Secondary emission of electrons by electrons and ions, as well as backscattering, determine the floating potential. These are both functions of the angle of incidence of particles on the surface.

In this work, the angular distribution of incident particles is obtained for attracted and repelled particles for cylindrical spacecraft. Results are given for the plane and spherical cases as well.

For isotropic spacecraft materials, the backscattering coefficients, the secondary emission coefficients, and the shielding efficiency depend on impact energy and impact zenith angle, but are independent of azimuth angle. Accordingly, only the distribution of impact zenith angles is important. For convenience, only protons will be considered, the extension to other charged particles being obvious. First the problem will be precisely defined, then a simplified model of physical reality set up, and, finally, the distribution of impact angles derived.

(Received for publication 12 May 1981)

2. DEFINITION OF PROBLEM

Find the flux, j_o, of protons striking an element of area ΔA with impact kinetic energies within the band $E \pm \Delta E/2$ and with impact zenith angles within the band $\theta \pm \Delta\theta/2$.

3. MODEL

The model is that of an infinitively long cylinder of radius R_o. Beyond a "sheath" of radius R_s, the plasma is isotropic and is at zero potential. The potential within the sheath is modeled by:

$$\Phi = \Phi_o \frac{\ln(R/R_s)}{\ln(R_o/R_s)} \quad . \tag{1}$$

The subscripts "o" and "s" will be used to indicate values of variables at R_o and R_s. No subscript will be used for general values of R.

In the model, the differential flux $f(E, \Phi)$ protons cm^{-2} sec^{-1} $ster^{-1}$ eV^{-1} is a function of kinetic and potential energies only — except in the "shadow" of the satellite where it is zero. Both potential (Φ) and kinetic (E) energy are expressed in electron volts. Any impact angle and energy corresponding to a trajectory originating elsewhere on the satellite is considered to be "shadowed."

4. DERIVATION OF IMPACT ZENITH ANGLE DISTRIBUTION

The impact proton flux is the product of four factors, namely: energy band width, unshadowed solid angle, projected area, and differential flux. This may be written as

$$j_o = (\Delta E)(\Delta\theta\, \phi_z \sin\theta_o)(\Delta A \cos\theta_o)[f(E_o, \Phi_o)] \tag{2}$$

where ϕ_z = total unshadowed azimuth angle. The solid angle is that which would be subtended at the earth's center by the area enclosed by latitudes $\theta_o \pm \Delta\theta/2$ and longitudes $\phi \pm \phi_z/2$. The azimuth angle will be taken as zero perpendicular to the cylinder's axis. If shadowing occurs, it will be at the larger angles.
Equation (2) may be rewritten as

$$j_o = [\Delta E\, \Delta\theta\, \Delta A\, f(E_o, \Phi_o)][\sin\theta_o \cos\theta_o][4\phi_m] \tag{3}$$

where ϕ_m = maximum unshadowed azimuth angle, ϕ being measured so as always to lie in the first quadrant. The factor 4 accounts for the four quadrants. A further rewriting yields

$$j_o = K \phi_m \sin 2\theta_o$$

$$K \equiv \frac{\Delta E}{2} \Delta\theta \Delta A \, f(E_o, \Phi_o) \tag{4}$$

$$0 \leq \phi_m \leq \pi/2 \quad .$$

Note: $\sin 2\theta_o \equiv 2 \sin\theta_o \cos\theta_o$.

Equation (4) is very general. The geometry of the spacecraft's surface and field enter into the equation only through ϕ_m, the maximum unshadowed azimuth angle.

5. SPECIAL CASES

For positive spacecraft potentials, the reverse trajectories curve away from the spacecraft; therefore, there is no shadowing and

$$\phi_m = \pi/2 \qquad \text{if } \Phi \geq 0 \quad . \tag{5}$$

From Eq. (4), the angular distribution is:

$$j_o = (\pi/2) K \sin 2\theta \quad .$$

The other special case is that of looking for protons of impossibly low energy. Here we may write

$$\phi_m = 0 \quad \text{if } \Phi_o < -E_o \quad , \tag{6}$$

which has meaning only for negatively charged spacecraft.

6. MAXIMUM UNSHADOWED AZIMUTH ANGLE

The simplest cases have been dealt with in the preceding section. This section will consider cases defined by:

$$-E_o < \Phi_o < 0 \quad . \tag{7}$$

The model has zero axial field. Therefore, the kinetic energy associated with the axial velocity component is independent of radial position and may be written:

$$E_a = E_o \sin^2 \phi_o \sin^2 \theta_o , \tag{8}$$

where E_o is the impact energy and ϕ_o and θ_o are the impact angles. This relationship follows from the breakdown of the impact velocity into four components, as shown in Figure 1. The model has a radial field about the cylinder's axis. Thus the tangential ($\perp$ to radial and axial directions) kinetic energy is subject to conservation of angular momentum and is given by:

$$E_t(R) = E_o(R_o/R)^2 \cos^2 \phi_o \sin^2 \theta_o \quad . \tag{9}$$

The radial kinetic energy is simply:

$$E_r = E \cos^2 \theta \quad . \tag{10}$$

The total proton energy is independent of the radius, and beyond the sheath it equals kinetic energy. The total energy is thus:

$$E = E_r + E_a + E_t + \Phi \quad , \quad \Phi < 0 \quad . \tag{11}$$

At the sheath's edge Eq. (11) becomes:

$$E = E_s \cos^2 \theta_s + E_o \sin^2 \phi_o \sin^2 \theta_o + (R_o/R_s)^2 E_o \cos^2 \phi_o \sin^2 \theta_o \tag{12}$$

and at the satellite's surface it becomes

$$E = E_o \cos^2 \theta_o + E_o \sin^2 \phi_o \sin^2 \theta_o + E_o \cos^2 \phi_o \sin^2 \theta_o + \Phi_o \tag{13a}$$

and

$$E_s = E_o + \Phi \qquad \Phi < 0 \; . \tag{13b}$$

The limiting case corresponds to a vanishing radial energy at the sheath's edge or to

$$\cos^2 \theta_s = 0 \quad . \tag{14}$$

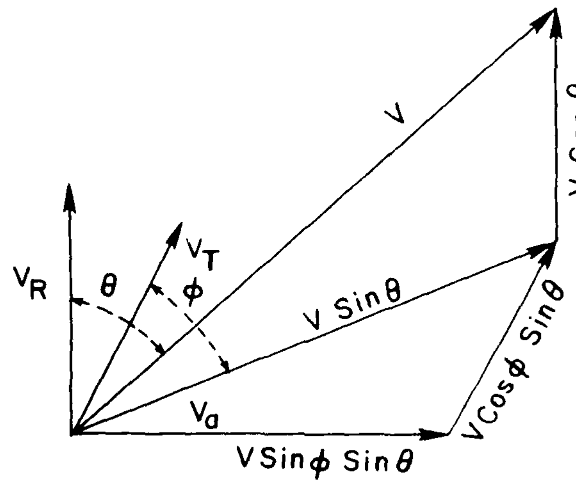

Figure 1. Velocity Components. The velocity V consists of a component ($V_R = V\cos\theta$) in the radial direction, a component ($V_a = V\sin\theta\sin\theta$) parallel to the axis, and a component ($V_T = V\cos\phi\sin\theta$) in the tangential direction perpendicular to the other components. An electric field exists only in the radial direction. θ and ϕ are the zenith and azimuth angles respectively

By inserting Eq. (14) into Eq. (12) and then equating the left-hand portion of Eqs. (12a) and (13b) the following is obtained:

$$\cos^2\phi = \frac{\Phi/E_o - \cos^2\theta}{[1 - (R_o/R)^2]\sin^2\theta} \quad . \tag{15}$$

Consideration of Eq. (15) and the trivial cases leads to a general equation for the maximum unshadowing azimuth angle ϕ_m. It is:

$$\cos^2\phi_m = \max\left[0\ ,\ \min\left(1\ ,\ \frac{\Phi/E_o - \cos^2\theta}{[1 - (R_o/R)^2\sin^2\theta]}\right)\right]$$

or (16)

$$0 < \phi_m = \cos^{-1}\left\{\max\ ,\ \left[0\ ,\ \min\left(1\ ,\ \frac{\Phi/E_o - \cos^2\theta}{[1 - (R_o/R_s)^2\sin^2\theta}\right)\right]\right\}^{1/2} < \frac{\pi}{2} \ .$$

Equations (4) and (16) together give the zenith angle (θ) distribution of protons striking the surface of a cylindrical satellite.

The angular distribution derivation given has considered only the potential at the inner ($R = R_o$) and outer ($R = R_s$) edges, not the potential within the sheath ($R < R_s$). It may be shown that the potential within the sheath is not controlling, provided that at all points within the sheath it is equal to or more negative than that of the inverse square potential function:

$$\Phi = \left[\frac{(R_s/R)^2 - 1}{(R_s/R_o)^2 - 1}\right] \cdot \Phi_o \quad , \quad \Phi_o < 0 \quad . \tag{17}$$

This function is adjusted to match the model at the sheath's edge. The logarithmic function of the model satisfies this condition. The proof is similar to that given for the spherical case for objects in a gravitational well. The proof is only valid if the potential is a function of radial position alone.

The distribution of impact zenith angles according to Eqs. (4) and (16) is shown in Figure 2 for several cases. The deviations from the symmetrical sin ($2\,\theta$) distribution are due entirely to shadowing. The shadowing is equivalent to a "horizon" at less than 90^o below the zenith due to refraction of the protons.

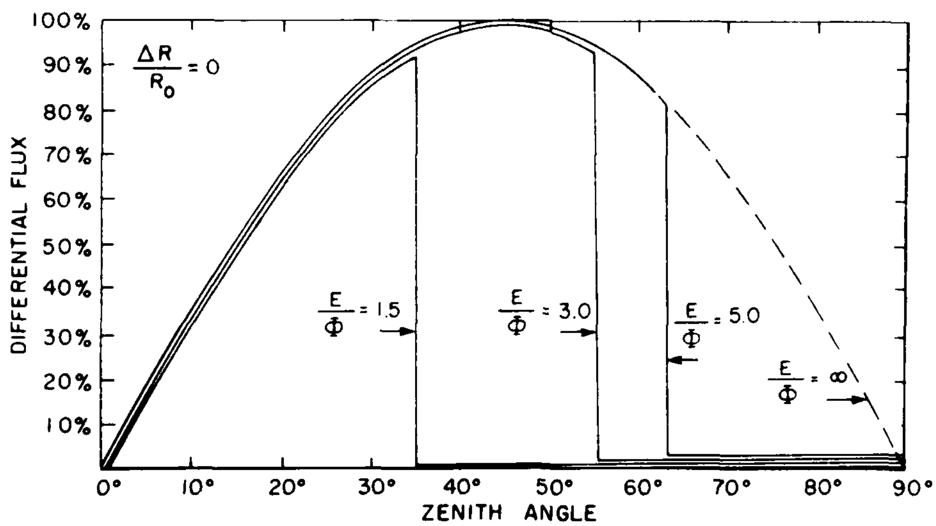

Figure 2. Distribution of Zenith Impact Angles for Protons on a Cylindrical Satellite: (a) Thin-Sheath Case

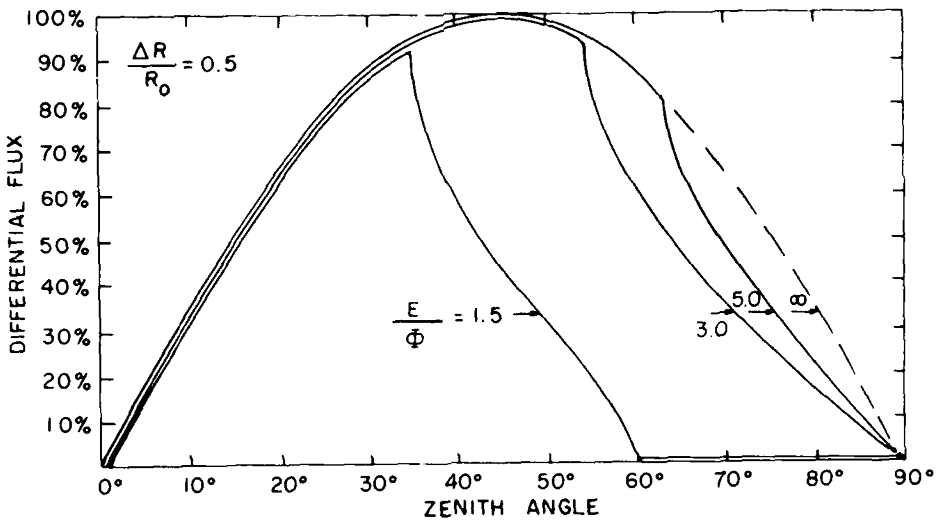

Figure 2. Distribution of Zenith Impact Angles for Protons on a Cylindrical Satellite: (b) Medium-Sheath Case

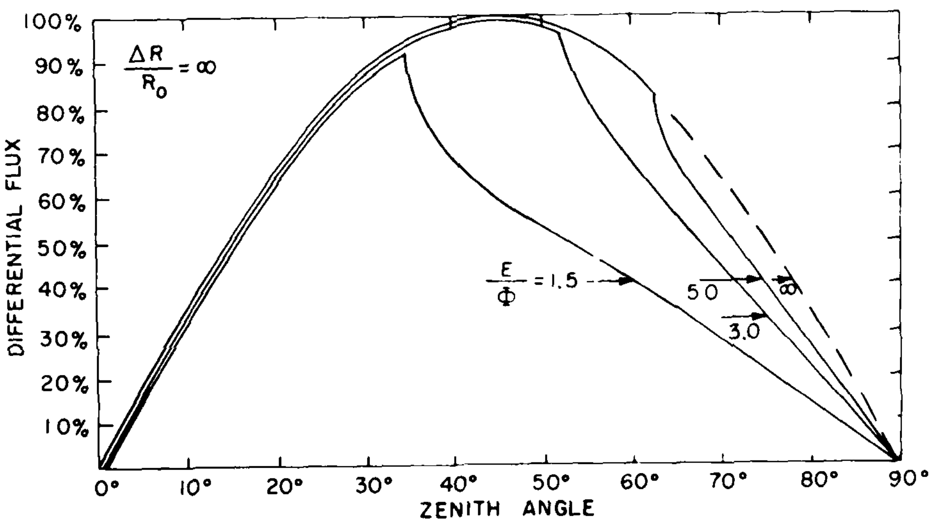

Figure 2. Distribution of Zenith Impact Angles for Protons on a Cylindrical Satellite: (c) Thick-Sheath Case

7. DISCUSSION

The theory given here is exact in that it is completely consistent with the model. The model, however, represents a physical impossibility in that the electric field is discontinuous at the surface of the sheath and an approximation in that end effects are taken to be vanishingly small. Only if the nearest end is at a distance very large compared to the radius will its effect become vanishingly small. The theory does, however, represent a limiting case and, as such, is useful.

8. SUMMARY

The angular distribution of impacting repelled particles is sin $(2\,\theta)$, as given by Eq. (4), since there is no shadowing for repelled particles. Electrons incident on a negatively charged surface and ions on a positively charged surface will impact in this way. In order to calculate surface potentials, taking account of secondary electron emission, one must know the distribution of impact angles as well as the secondary electron yield as a function of angle.

The angular distribution of impacting attracted particles (electrons on a positive *surface*, and positive ions on a negative surface) is more complicated. The impacting angular distribution for a cylindrical surface for attracted particles has been derived here, as shown in Figures 2 (a), 2 (b), and 2 (c), for a range of energies and sheath thickness.

The distribution of impact angles (attracted particles) for a plane surface is the same as the case of zero sheath thickness. For this case the distribution is proportional to sin $(2\,\theta)$ for θ less than θ_m, where

$$\theta_m = \cos^{-1} (\Phi/E)^{1/2} \quad ,$$

and where E is the impact energy. If θ is greater than θ_m, the distribution function is zero. For spherical surfaces there is no shadowing, so the distribution is again proportional to sin $2\,\theta$ in the thick sheath limit.